Modeling a Nonlinear Stiffness Isolation System Using NOLIN Entries in a Modal Transient Analysis for the Mars 2020 Rover

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Modeling a Nonlinear Stiffness Isolation System Using NOLIN Entries in a Modal Transient Analysis for the Mars 2020 Rover

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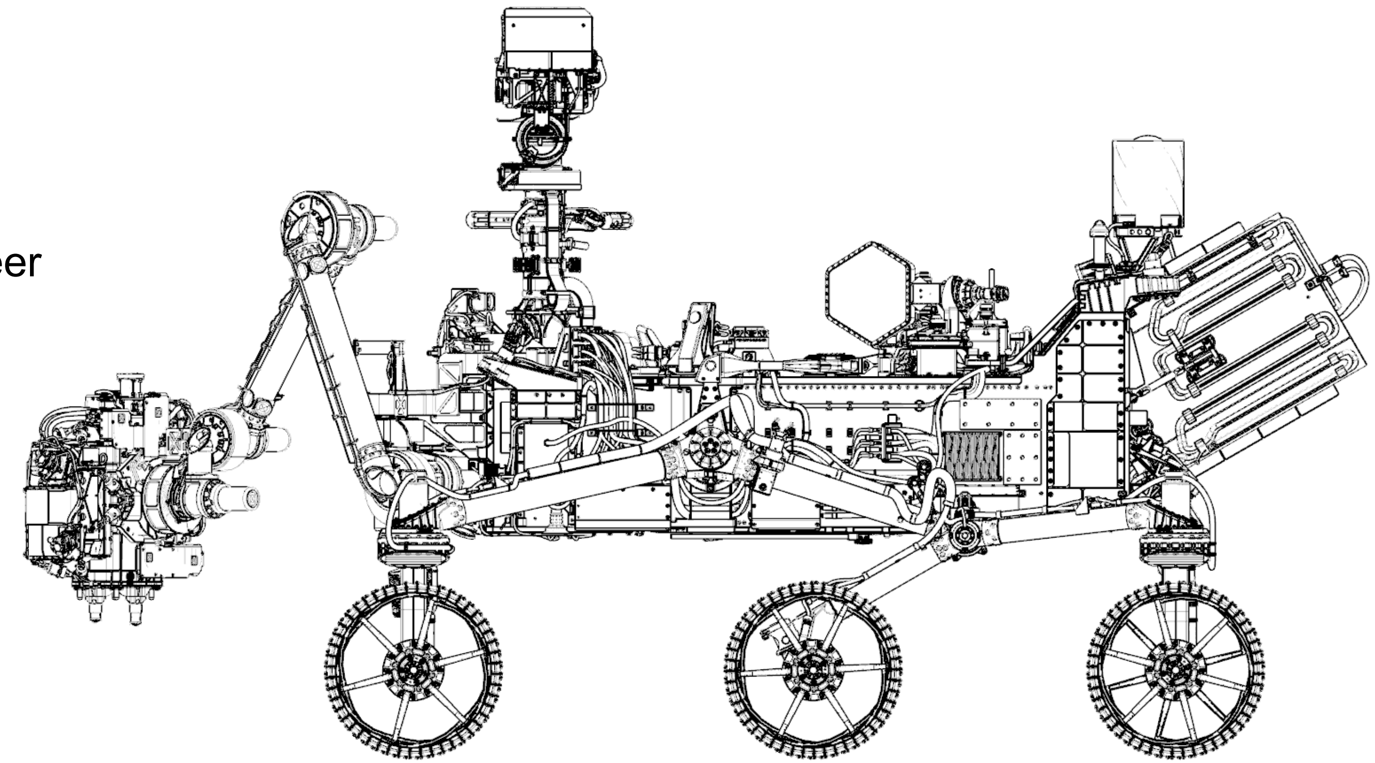
Sample Caching System Lead Structural Engineer



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Outline

- SHERLOC Overview
- SHERLOC Isolation System Overview
- Summary of Test Configurations
- Test Data Results
  - Single Strut Static Loading
  - Single Strut Dynamic Sine Burst Loading
  - Single Strut Dynamic Random Vibration Loading
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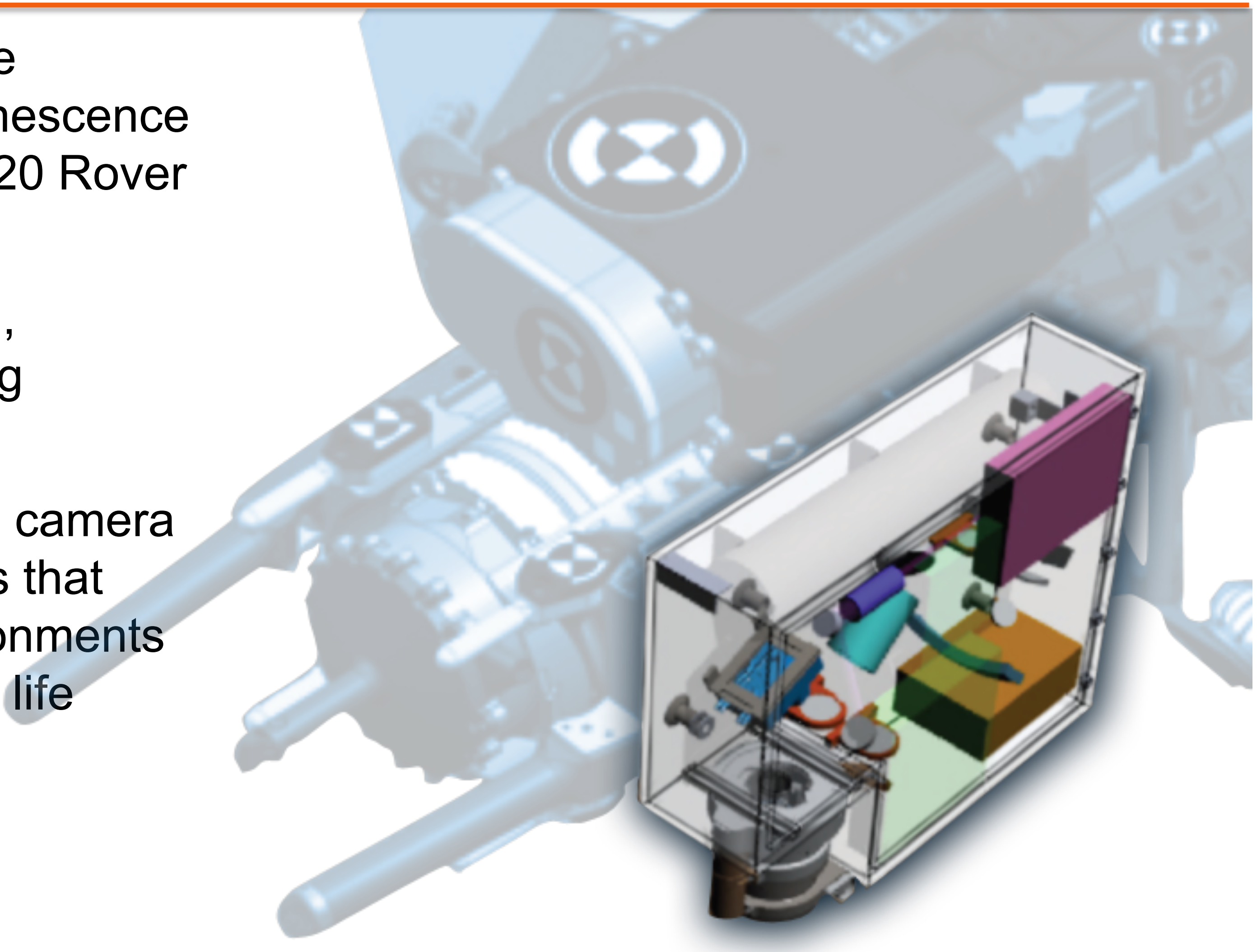
- Design Loads Modeling
- Test Data Correlation Modeling
  - Spectral Density Comparison
  - Time History Comparison
- Conclusions

SHERLOC Overview

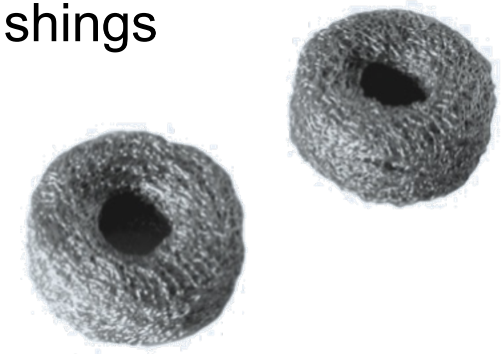
- SHERLOC: the Scanning Habitable Environments with Raman & Luminescence for Organics & Chemicals Mars 2020 Rover instrument
- Mounted on the rover's robotic arm, adjacent to the rock coring/abrading percussion drill
- Uses spectrometers, a laser, and a camera to search for organics and minerals that have been altered by watery environments and may be signs of past microbial life



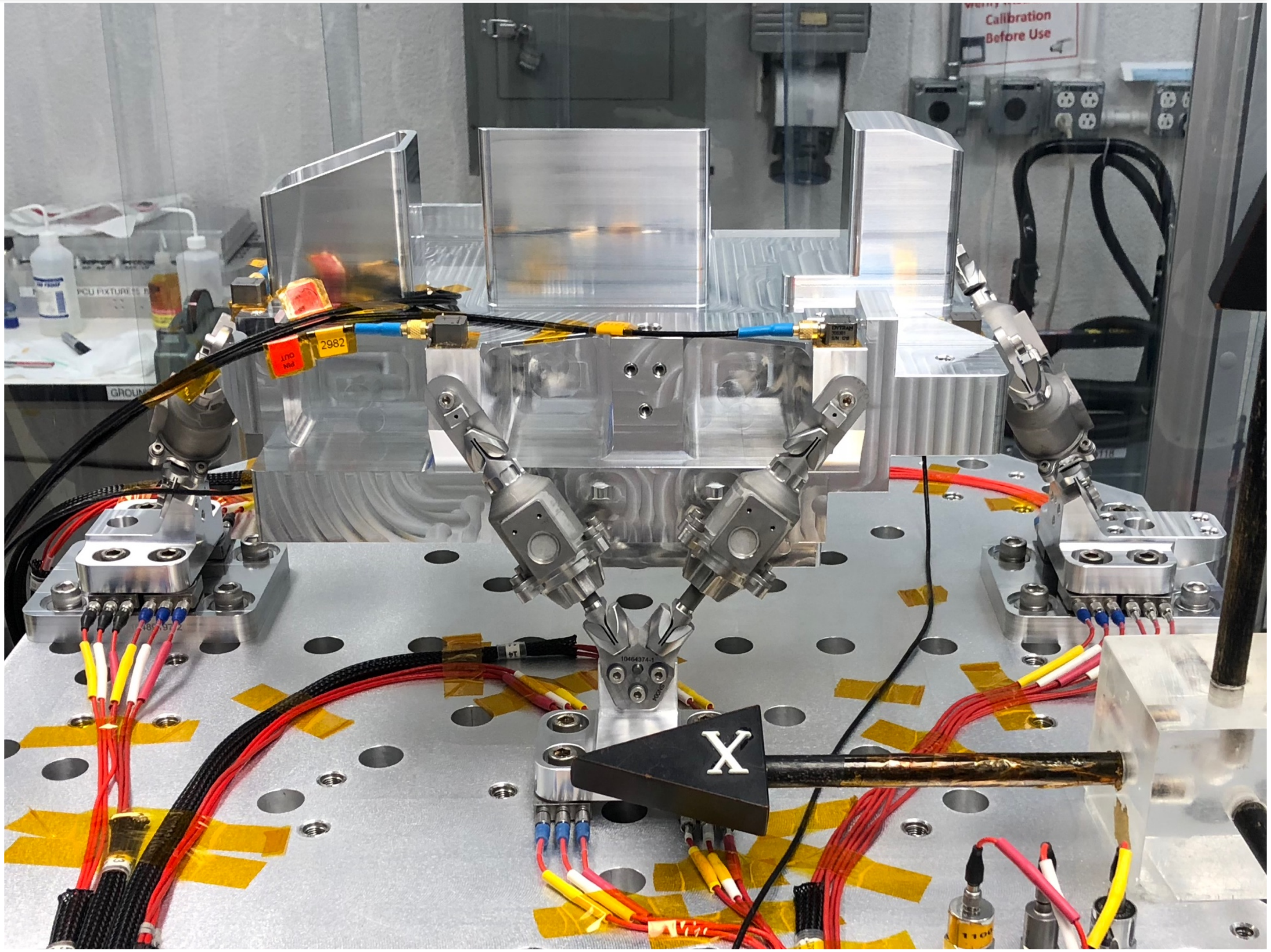
(Artist's Rendition)

SHERLOC Isolation System

- An isolation system was desired to reduce the percussion drilling high frequency vibratory environment transmissibility into the SHERLOC instrument
- A hexapod is used with piston struts supported through a pair of compliant wire mesh rectangular toroid isolation bushings



Example Wire Mesh Bushings



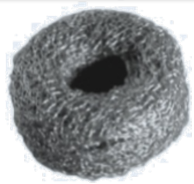
SHERLOC Isolation System with Mass Model on Shaker Table

Test Configurations

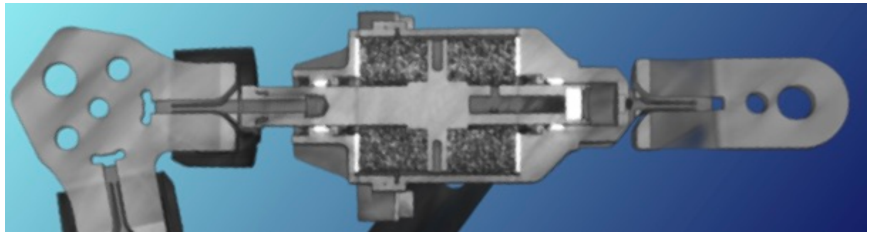
Testing was performed at three stages of assembly:

- Single Bushing Static Compression Test
- Strut Level:
  - Static Test
  - Dynamic Sine Burst Test
  - Dynamic Random Vibration Test
- Hexapod Level Random Vibration Test
- Single Bushing Level Compression Testing

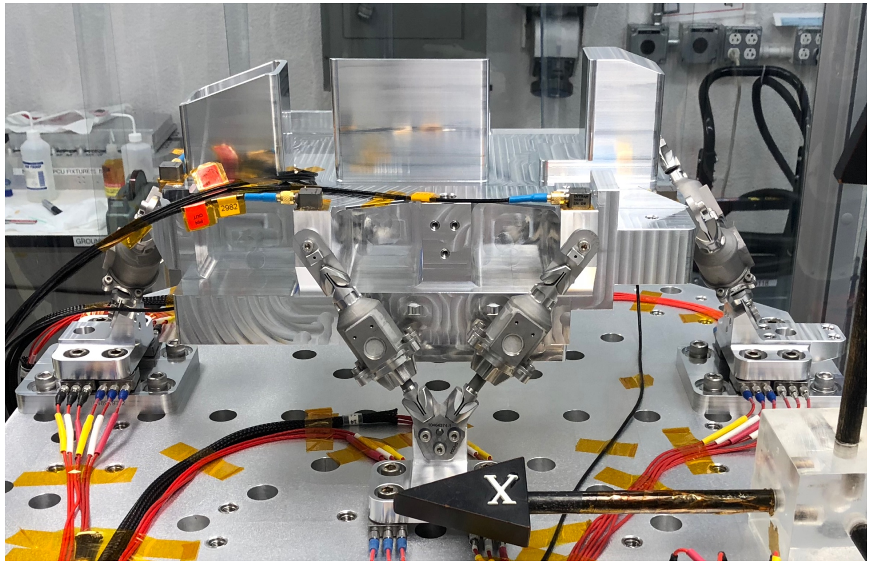
(Two different bushing stiffness pairs are used in the hexapod design; this presentation focuses on the stiff pair.)



Single Bushing Level



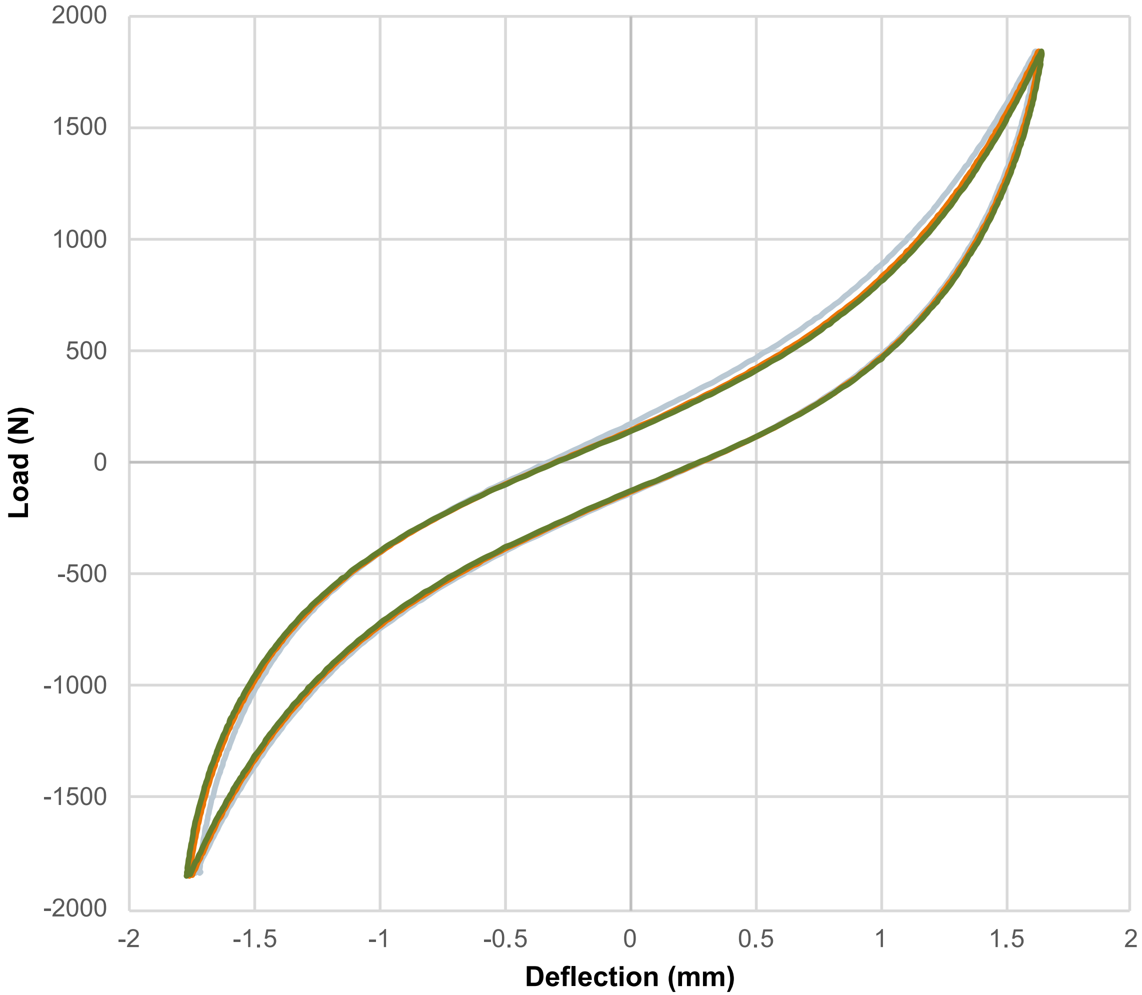
Single Strut Level (CT Scan Image)



Hexapod Level

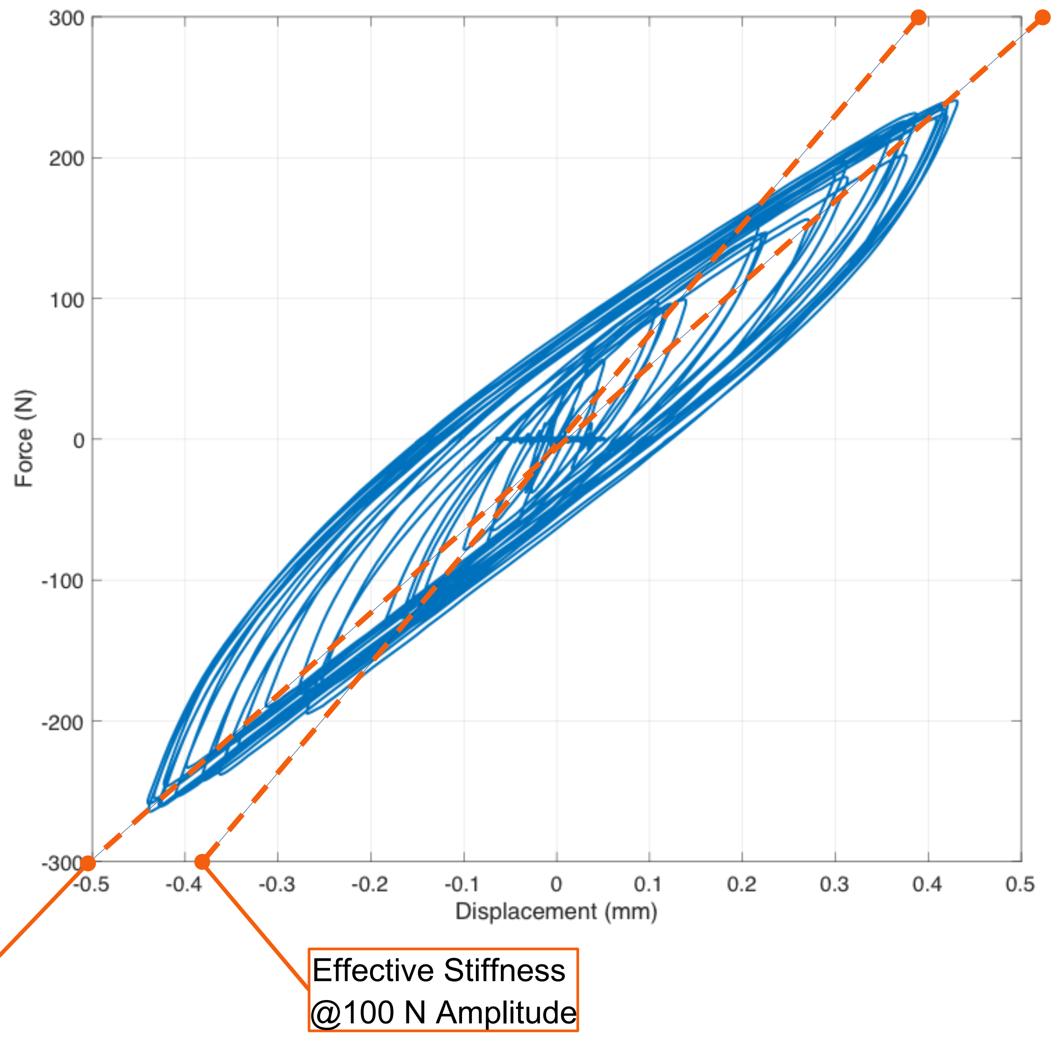
Single Strut Static Test Results

- Configuration: Two wire mesh bushings were assembled into a canister supporting a piston with the prescribed bushing preload (enforced deflection)
- Loading:
  - The piston was loaded from -1840 N to +1840 N
  - Three load cycles applied at a rate of 0.15 mm/sec
- Observations:
  - Significant stiffening at high amplitudes (>700 N)
  - ~260 $N_{P\text{-}V@0\text{-}mm}$ of (presumed rate independent) hysteresis between loading and unloading directions



Single Strut Dynamic Sine Burst Test Results

- Configuration:
  - Two wire mesh bushings were assembled into a canister supporting a piston with the prescribed bushing preload (enforced deflection)
  - A mass was supported by the strut producing an effective first mode natural frequency of ~40 Hz for a moderate strut stroke
- Loading: A sine burst pulse consisting of 15 periods with a peak load of 250 N
- Observations:
  - ~150 $N_{P\text{-}V@0\text{-}mm}$ of hysteresis between loading and unloading directions
  - The hysteresis loop effective stiffness appears to soften with increased amplitudes in this load range



Single Strut Dynamic Random Vibration Test Results

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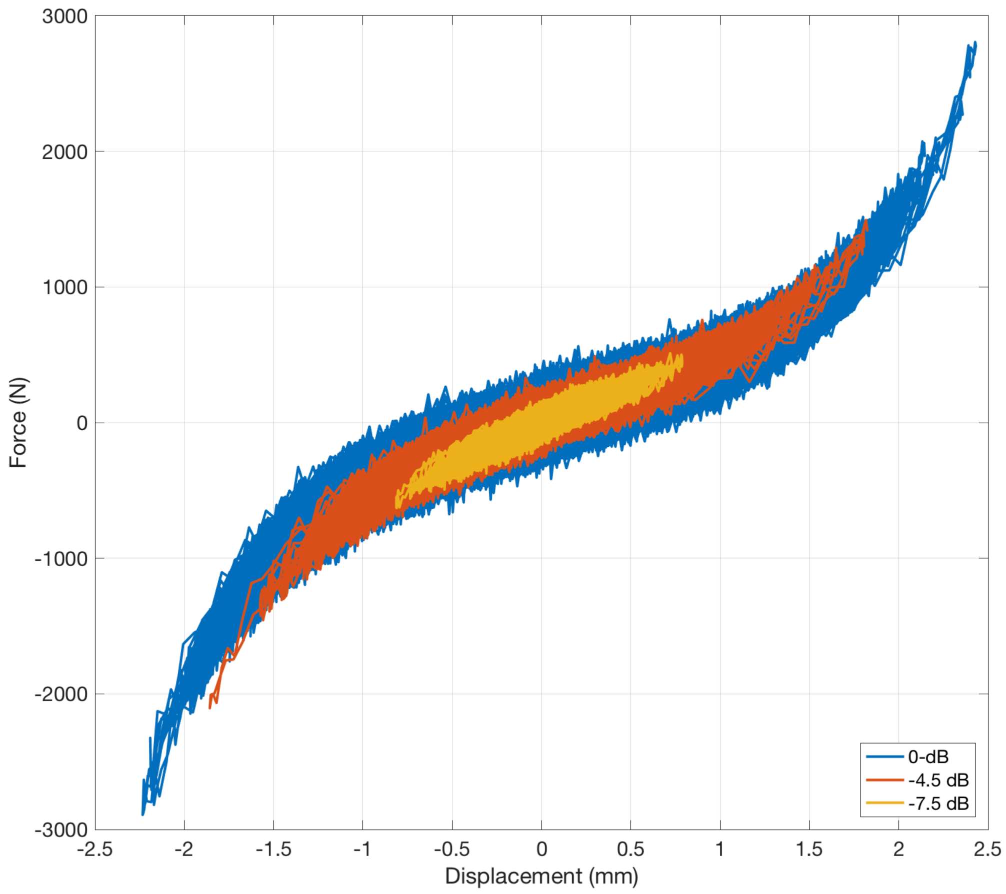
- Configuration:
  - Two wire mesh bushings were assembled into a canister supporting a piston with the prescribed bushing preload (enforced deflection)
  - A mass was supported by the strut producing an effective first mode natural frequency of ~40 Hz for a moderate strut stroke
- Loading:
  - Typical “top-hat” random vibration profile from 20-2000 Hz
  - Excitation levels incremented up to an RMS load of 292 N_{RMS}
- Observations:
  - Very similar shape to the single strut static load vs. deflection data
  - ~660 $N_{P\text{-}V@0\text{-}mm}$ of hysteresis between loading and unloading directions in 0-dB data (significantly more than static test data)
  - Apparent increase in hysteresis with increased excitation amplitude, but less proportional than pure viscous damping



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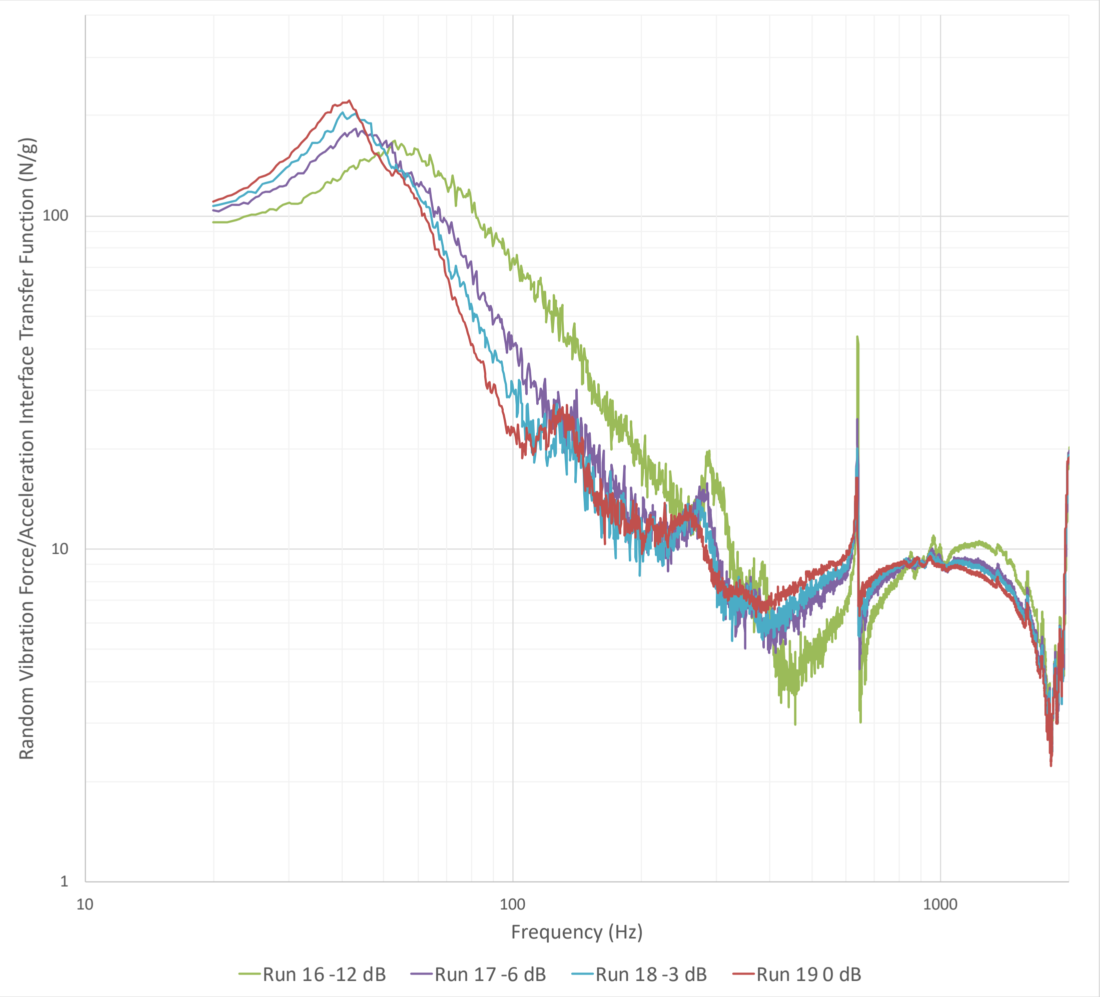
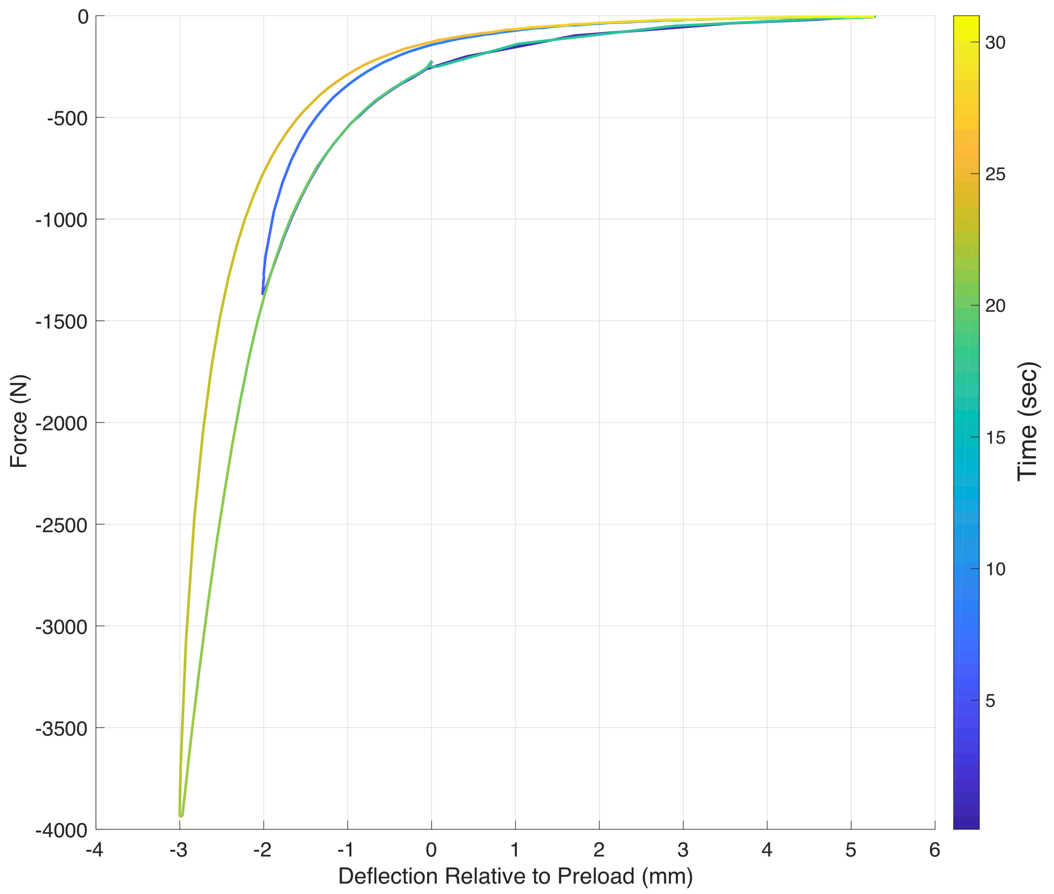
Hexapod Dynamic Random Vibration Test Results

- Configuration: A SHERLOC mass model is supported through six struts
- Loading:
  - Typical “top-hat” random vibration profile from 20-2000 Hz producing
  - Excitation levels increased in 3-dB increments up to the full specification level
- Observations:
  - The apparent primary natural frequency dropped from 55 Hz @ -12 dB to 41 Hz @ 0 dB
  - Apparent damping of the primary natural frequency also dropped from Q=1.7 @ -12 dB to Q=2.2 @ 0 dB



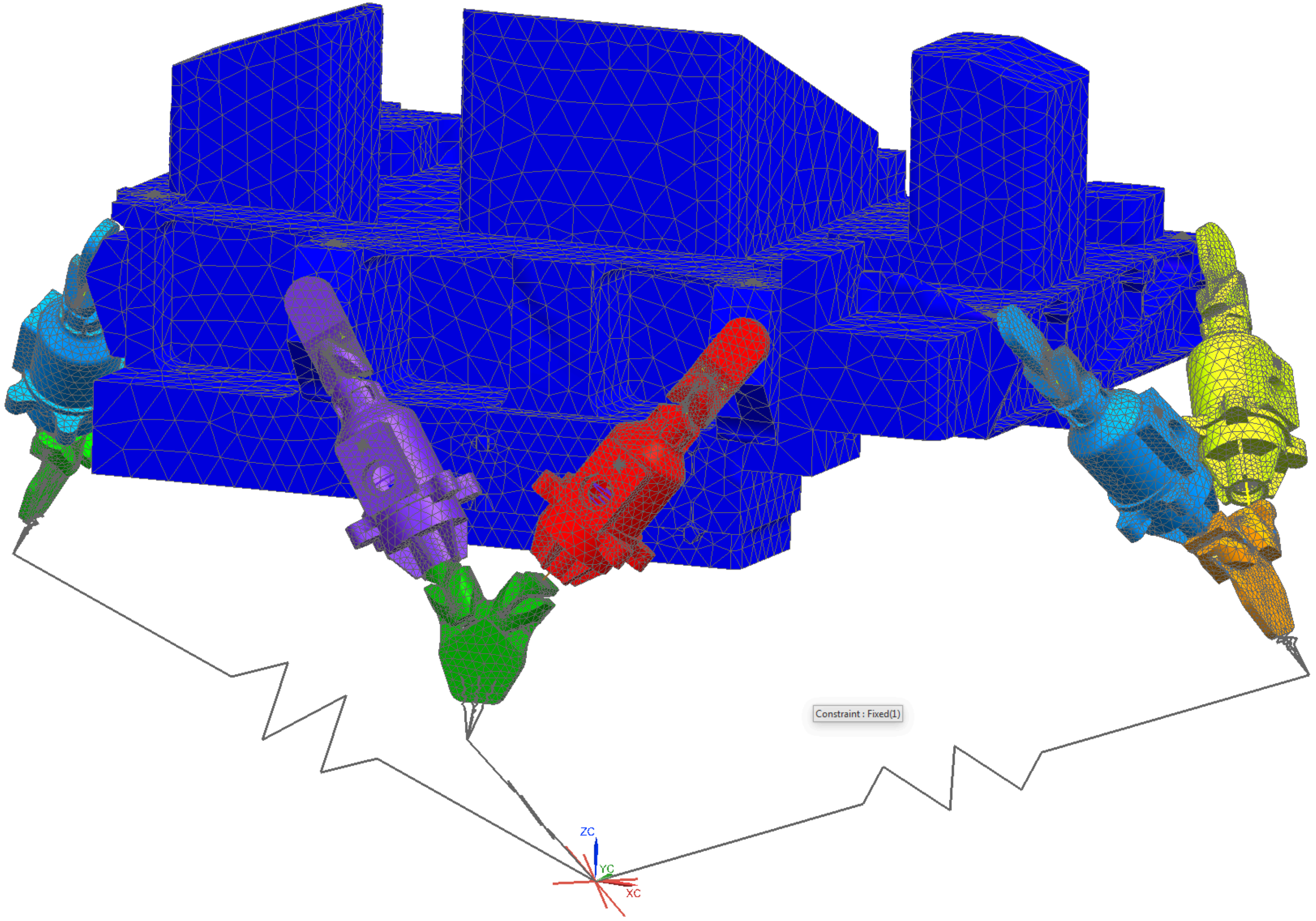
Single Wire Mesh Bushing Compression Test Results

- Configuration: A single wire mesh bushing sandwiched between two stiff surfaces
- Loading:
  - Run 1: 2 mm enforced displacement in three increments:
    1. Nominal compression preload (~5.2 mm)
    2. Compression of an additional 2 mm
    3. Removal of load
  - Run 2: 3 mm enforced displacement in three increments:
    1. Nominal compression preload (~5.2 mm)
    2. Compression of an additional 3 mm
    3. Removal of load
- Observations:
  - The 2 mm and 3 mm loadings follow nearly the same load vs. deflection curve
  - Both exhibit hysteresis during load removal
  - The 3 mm load removal curve does not meet the 2 mm load removal curve until -1.5 mm deflection point



SHERLOC Isolation System Finite Element Model

- Tetrahedral elements used for mass model and strut housings
- Beam elements used for piston
- Single beam element used for each wire mesh isolation bushing
- The design loads model utilized a linearized stiffness for the wire mesh bushing derived from single strut random vibration testing



Design Loads Model
Modal Results

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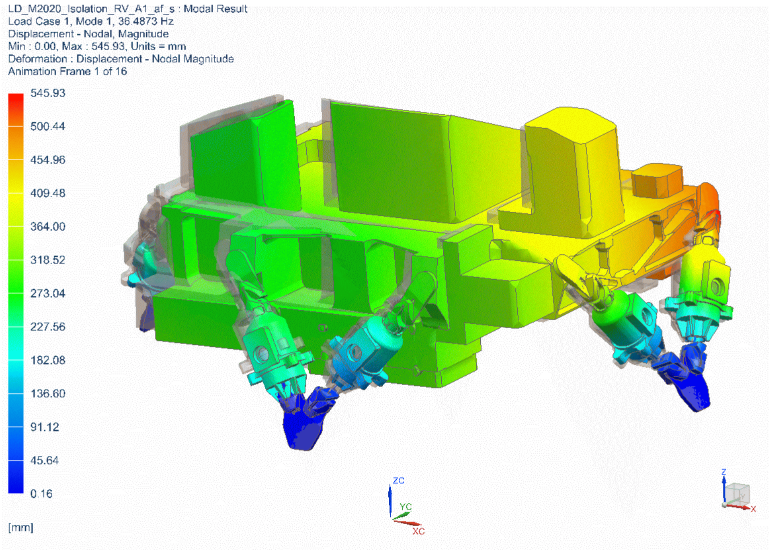
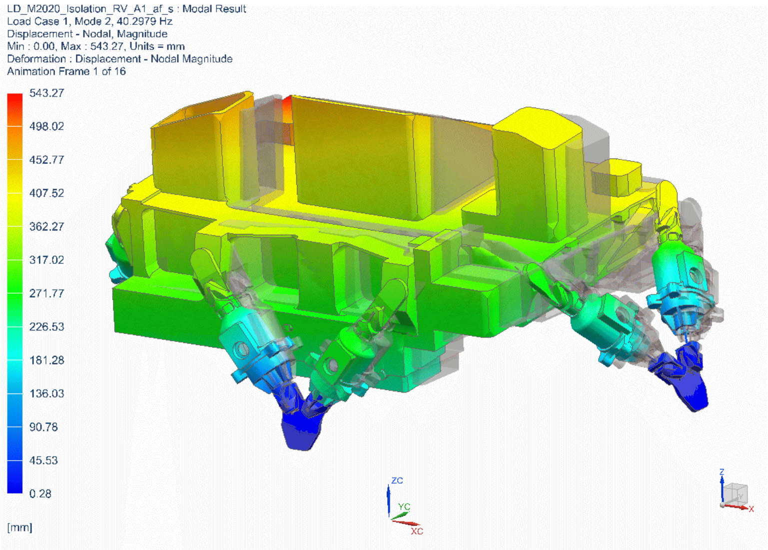
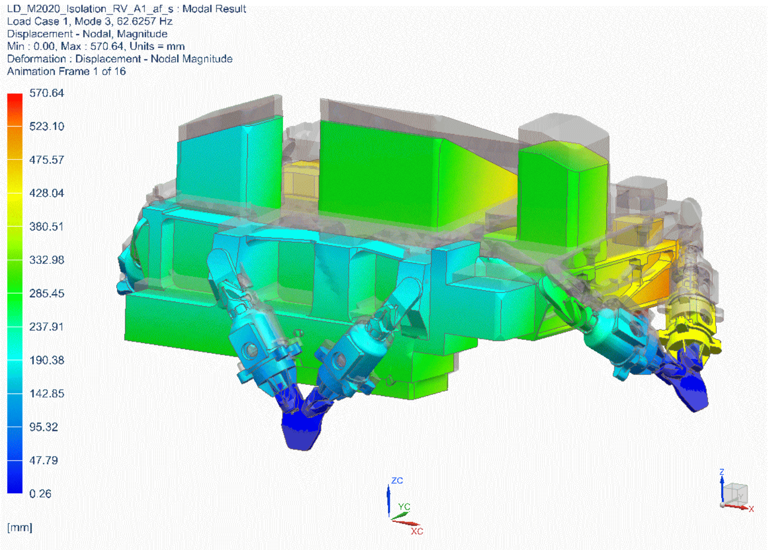


Mode 1, 36.5 Hz



Mode 2, 40.3 Hz

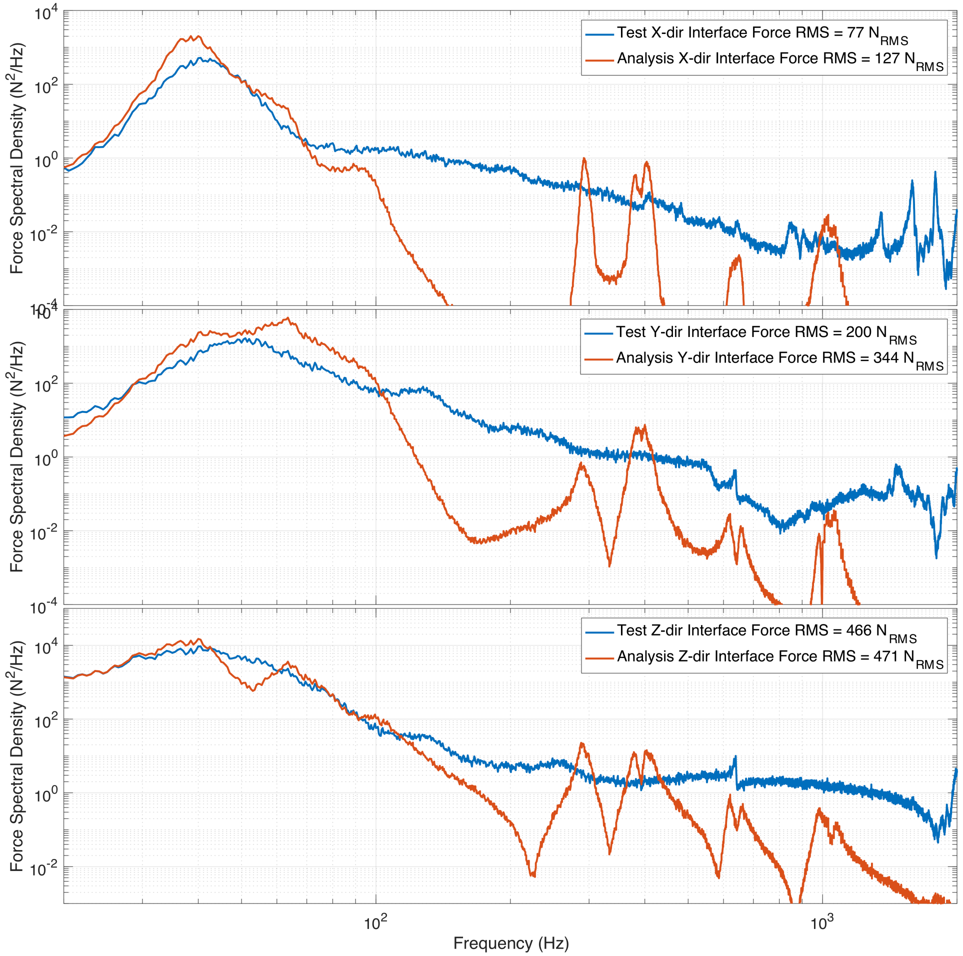


Mode 3, 62.6 Hz

The majority of the effective mass (>65%) is captured in the first three modes of the system.

Design Loads Model Z-Direction Hexapod Random Vibration Spectral Density Correlation to Test Results

- Model Configuration:
  - SHERLOC mass model is supported through six struts
  - Design loads model assumed 10% modal damping for the 6 isolation modes, 1.5% modal damping for all other modes
- Loading:
  - Typical “top-hat” random vibration profile from 20-2000 Hz producing
  - The test data input acceleration spectral density was used as the model excitation to provide a more apples-to-apples comparison (Full specification level compared)
- Observations:
- The model matches the test data fairly well below 100 Hz
  - Two distinct modes under 100 Hz are observed in the analysis model whereas the test data shows evidence of only a single mode
  - More effective damping is observed in the test data
- Overall force RMS values are conservative for the analysis model, more so in the off-axis directions
- The model predicts more apparent mass roll-off than the test data exhibit resulting in poor correlation beyond 100 Hz



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Nastran Bulk Data Entries for SOL 112 Nonlinear Load vs. Deflection

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Element to augment with nonlinear load	CBEAM	10	10	1	2	0.	0.	1.	
Measurement EPOINT	EPOINT	11							
Applied/Opposite load EPOINTs	EPOINT	12							
	EPOINT	13							
Relative displacement measure TF	TF	100	11	0	1.				
		1	1	1.					
		2	1	-1.					
Applied load transfer to node TF	TF	100	1	1	1.				
		12	0	-1.					
Ground applied load EPOINT TF	TF	100	12	0	1.				
Opposite load transfer to node TF	TF	100	2	1	1.				
		13	0	1.					
Ground opposite load EPOINT TF	TF	100	13	0	1.				
Nonlinear load vs. deflection entries	NOLIN1	101	12	0	1.	11	0	3000	
	NOLIN1	101	13	0	1.	11	0	3000	
Nonlinear load vs. velocity entries	NOLIN1	101	12	0	30.	11	10	1000	
	NOLIN1	101	13	0	30.	11	10	1000	
Alternate nonlinear load vs. velocity entries (commented out)	$ NOLIN3	101	12	0	30.	11	10	0.	
	$ NOLIN4	101	12	0	30.	11	10	0.	
	$ NOLIN3	101	13	0	30.	11	10	0.	
	$ NOLIN4	101	13	0	30.	11	10	0.	

Table ID for Nonlinear Load vs. Deflection

Table ID for Step Function Load vs. Velocity

Nonlinear features are not activated in SOL 112 with the default ENFMOTN system cell, use ENFMOTN=1 or 2.

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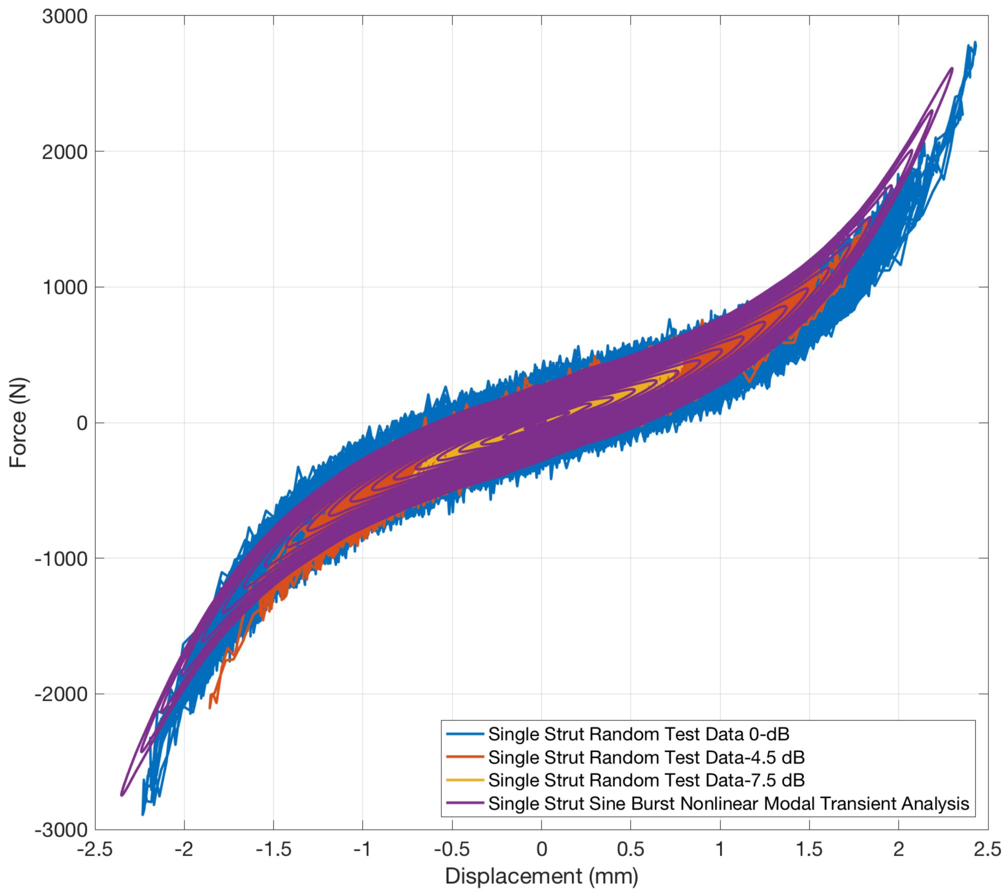
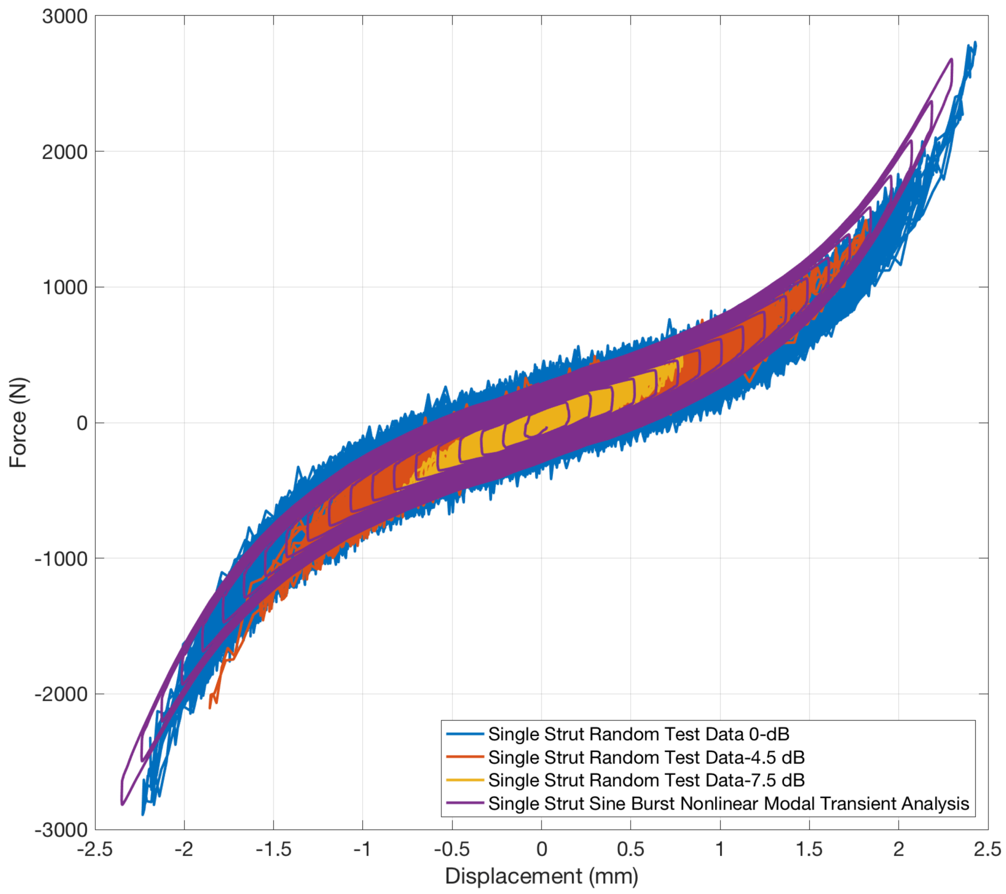
Single Strut Sine Burst Modal Transient No Friction Correlation to Test Results

- Model Configuration:
  - Modal and tuned structural damping (applied to the wire mesh bushing material) employed
  - A single strut was modeled with a NOLIN entry at each wire mesh bushing to augment the load deflection curve into its nonlinear shape
- Loading: A 40 Hz sine burst enforced motion up to 2.4 mm
- Observations (comparing random test data to sine burst analysis data):
  - Fairly good match of the overall nonlinear stiffness
  - The use of modal and/or structural damping does not produce the effective stiffening at low amplitudes observed in test



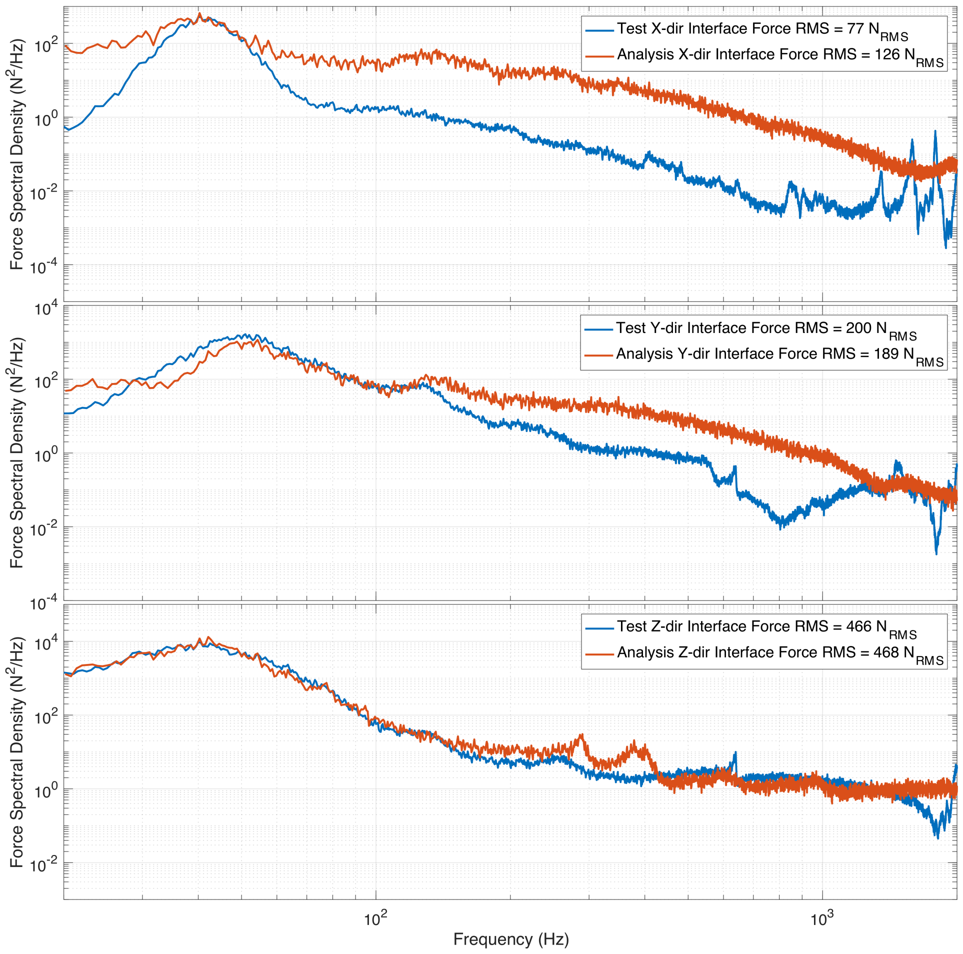
Single Strut Sine Burst Modal Transient With Friction Correlation to Test Results

- Model Configuration:
  - Modal and tuned structural damping (applied to the wire mesh bushing material) employed
  - A single strut was modeled with two NOLIN entries at each wire mesh bushing
    - One used to augment the load deflection curve into its nonlinear shape
    - One used to apply time invariant hysteresis (akin to idealized friction)
- Loading: A 40 Hz sine burst enforced motion up to 2.4 mm
- Observations (comparing random test data to sine burst analysis data):
  - Fairly good match of the overall nonlinear stiffness and hysteresis
  - The friction simulated in the strut provides the amplitude softening observed in the hexapod test data
  - Idealized friction is much more abrupt than behavior observed in the test data
    - Leads to much higher effective damping for low amplitude responses
    - A means to better tailor the time invariant hysteresis has not yet been discovered within the TF/NOLIN features available



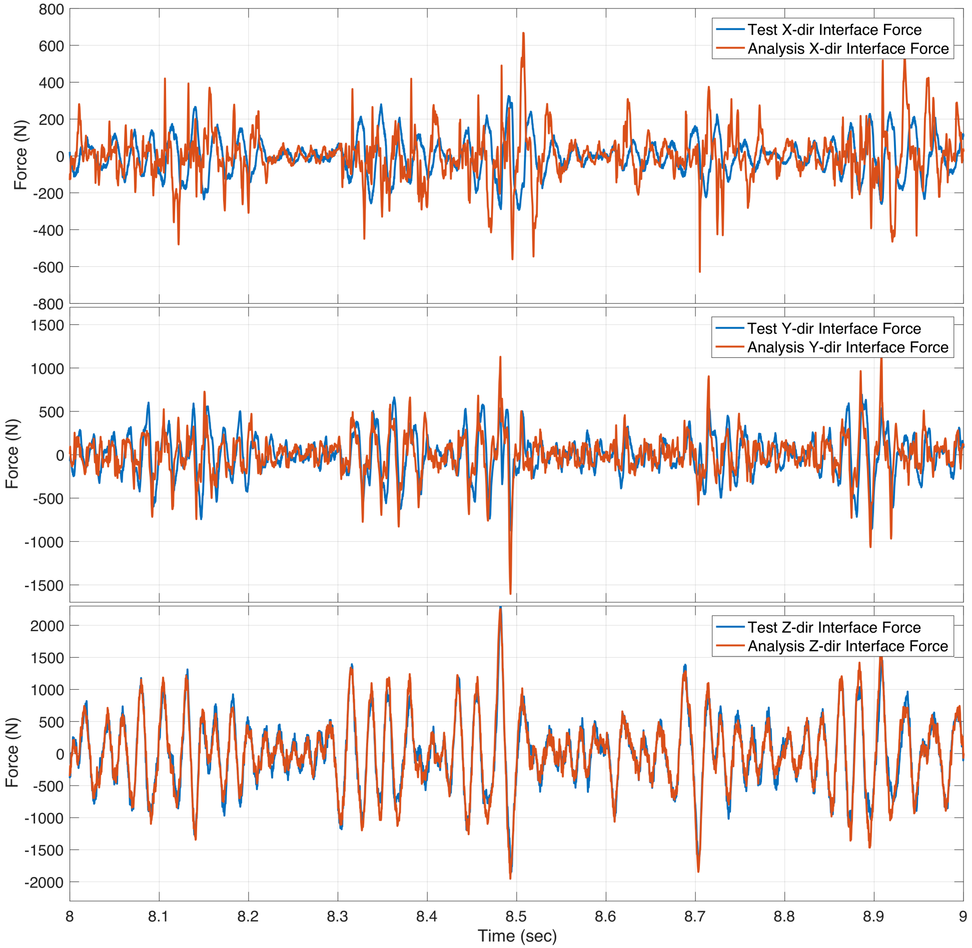
Hexapod Random Vibration Nonlinear Modal Transient Spectral Density Correlation to Test Results

- Model Configuration:
  - SHERLOC mass model is supported through six struts
  - Modal damping at 3% applied to all modes
  - Tuned structural damping (applied to the wire mesh bushing material) employed
  - NOLIN entries at the wire mesh bushings used to:
    - Simulate nonlinear load vs. deflection curve
    - Coarsely simulate the time invariant hysteresis
- Loading:
  - Typical "top-hat" random vibration profile from 20-2000 Hz producing
  - (Full 0-dB specification level compared)
- Observations:
  - The model matches the in-axis (Z-direction) test data very well across the entire frequency range
  - The remaining two axes match fairly well near the first resonance, but have significantly higher response above 100 Hz (possibly overly damped)



Hexapod Random Vibration Nonlinear Modal Transient Time History Correlation to Test Results

- Model Configuration:
  - SHERLOC mass model is supported through six struts
  - Modal damping at 3% applied to all modes
  - Tuned structural damping (applied to the wire mesh bushing material) employed
  - NOLIN entries at the wire mesh bushings used to:
    - Simulate nonlinear load vs. deflection curve
    - Coarsely simulate the time invariant hysteresis
- Loading:
  - Typical "top-hat" random vibration profile from 20-2000 Hz producing
  - (Full 0-dB specification level compared)
- Observations:
  - The model matches the in-axis (Z-direction) test data very well
  - The remaining two axes match less well (especially X-direction) with high frequency spikes in the data
  - Spikes are likely due to the abrupt nature of the modeled time invariant hysteresis compared to the more gradual response observed in the single strut test data



Conclusions

- The use of NOLIN entries in a modal transient solution (SOL 112) is a powerful tool for efficient structural analysis requiring discrete nonlinear elements.
- SOL 112 is an efficient means of simulating transient dynamics of large models excited in the low to mid frequency range
- The use of NOLIN entries in SOL 112 allows for a crawl-walk-run approach to the analysis
  - Typically a frequency domain analysis (SOL 111) is utilized for preliminary design, the modal transient method allows for the same modal damping parameters to be employed.
  - Nonlinear load vs. deflection responses may be added into the model; though not presented here, NOLIN entries may also be employed to model more abrupt phenomenon such as preloaded or non-preloaded gapping
  - The modal transient method allows for additional damping options when the situation warrants:
    - Structural damping
    - Some ability to employ friction damping through NOLIN entries
- Though not an ideal correlation, the employment of a nonlinear modal transient solution has provided a much better understanding of the dynamic behavior of the SHERLOC Isolation system

Acknowledgements

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- SHERLOC Isolation System test data provided by JPL engineers Brian Franz, Elizabeth Duffy, and James Burdick
- Introduction and guidance on TF and NOLIN Nastran entries provided by Paul Blellock, Samuel Dyas, and Greg Mathy of ATA Engineering.

Backup

Abstract

The SHERLOC instrument on the Mars 2020 Rover is mounted adjacent to the rover’s rotary percussive drill. To prevent large vibratory excitations from being transmitted into the instrument, SHERLOC is mounted using a hexapod with wire mesh toroid compliant elements in the struts providing the major compliance and damping sources for the system. These wire mesh elements have a nonlinear load verses deflection behavior. When preloaded in pairs, they behave in a fairly linear fashion for moderate amplitudes, but then stiffen at large amplitudes. Random vibration testing of the isolated SHERLOC system was found to produce higher than usual crest factors for the full level excitation. Investigation of the data from the test revealed that the nonlinear behavior of the struts may be significantly affecting the response of the system. The test configuration was modeled in Simcenter. Nastran was used to compute the random vibration response of the model and the linear modal transient response. To simulate the nonlinear dynamics, Nastran NOLIN1 entries were added to the model to produce the nonlinear portion of the load verses deflection curves for each wire mesh element. The resulting nonlinear dynamic behavior better matched the test data and allowed for further investigation of the system with confidence. The use of NOLIN1 entries provides a powerful and efficient means of modeling nonlinear load verses deflection dynamic behavior in an otherwise linear system. This presentation proves an example use case along with the setup of EPOINT, TF, and NOLIN1 entries used to produce the desired behavior.